SPECTRAL RESPONSE OF A MARTIN-PUPLETT INTERFEROMETER FOR ELECTRON BUNCH LENGTH MEASUREMENTS

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Abstract

At the ELBE Free Electron Laser (FEL) at Forschungszentrum Dresden Rossendorf (FZD) electron bunches having lengths between 1 to 4 ps are generated. It is required to compress these electron bunches to lengths below 1 ps which necessitates diagnosis of the electron bunch parameters. We use a Martin-Puplett interferometer (MPI) which is a modification of the Michelson interferometer, where the beams are linearly polarized at specific orientations. It measures the autocorrelation function of the coherent transition radiation (CTR) from a view screen which is an optical replication of the electron bunch.

The interferometer setup consists of various optical components like polarizers, beam splitter, mirrors and Golay cell detectors. In our measurement a wire grid was used as a polarizer and also as a beam splitter. A thorough understanding of the response of the optical components, as a function of the CTR wavelength range of our interest, is required for correct analysis of the measured signal. We have therefore simulated the response of the entire interferometer setup including the diffraction losses and the window transmission and compared the results to experimental measurements.

INTRODUCTION

ELBE is based on a superconducting electron linac. The ELBE linac is designed to operate with an accelerating field gradient of 10 MV/m so that the maximum design electron beam energy at the exit of the second module is 40 MeV. ELBE delivers an electron beam with an average current of up to 1 mA. The electron source is a DC thermionic triode delivering beam with energy of 250 keV. The gun beam quality predefines the accelerated beam quality. In the ELBE the electron bunch is compressed to 10 ps after the electron beam injector. In the accelerator the electron bunch length is in the range of 1 to 10 ps. We use a Martin-Puplett interferometer (MPI) which is a modification of the Michelson interferometer, where the beams are linearly polarized at specific orientations. It measures the autocorrelation function of the coherent transition radiation (CTR) from a view screen which is an optical replication of the electron bunch.

In our work we want to determine the workable wavelength range for our Martin-Puplett interferometer setup. We have therefore simulated the response of the entire experimental setup. We also describe in this study our measurements of the electron bunch length, which is in the picosecond range. The bunch length is estimated from a frequency domain fit of a specially constructed analytical function to the measured power spectrum of the bunch. The power spectrum is obtained as a Fourier transform of the measured autocorrelation function of the CTR. The CTR autocorrelation function is measured with the help of a Martin-Puplett interferometer.

EXPERIMENTAL SETUP

A polarizing Martin-Puplett interferometer (shown in Fig. 1) is used to analyze the spectrum of the far-infrared radiation. CTR passes through a quartz window and is reflected by a parabolic mirror. Then the CTR is polarized vertically by a wire-grid linear polarizer and made incident on a beam splitter. For our measurements the wire grids are wound from 20 μm gold plated tungsten wire with 100 μm spacing (from center to center), which are used as polarizers and beamsplitters. The reflected beam from the beamsplitter then goes to a roof mirror which is fixed, while the transmitted beam goes to a movable roof mirror. These two reflected beams then interfere and then split by a second beam splitter (analyser) the polarization directions are detected using two Golay cell infrared (IR) detectors.

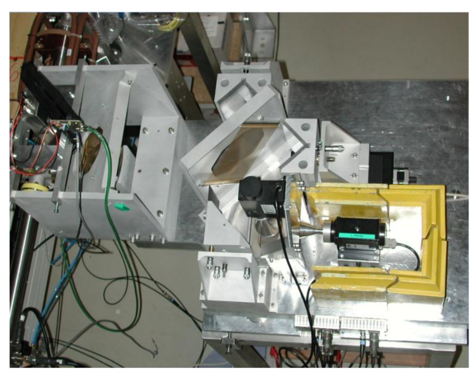

Figure 1: Martin-Puplett Interferometer.

GENERAL DESCRIPTION OF TRANSITION RADIATION

In our experiment the transition radiation is generated when the electron beam is impinged on an aluminum target rotated by 45^0 with respect to the incoming beam (shown in Fig. 2). The spectral energy flux of backward transition radiation is given for electrons by the Ginzburg-Frank formula [1]:

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$$\frac{d^2 I}{d\nu d\Omega} = \frac{e^2}{2\pi \in_0 c} \frac{\beta^2 \sin^2(\theta)}{(1-\beta^2 \cos^2(\theta))^2} \quad (1)$$

where I is the spectral energy flux in a solid angle $d\Omega$, β is the ratio of electron velocity to velocity of light (v/c) and θ is the polar angle with respect to the backward transition radiation.

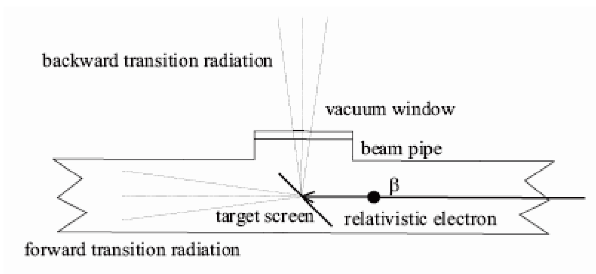

Figure 2: Emission of transition radiation.

The polar angles (opening angle) of the transition radiation for different beam energies are calculated using the above formula (1). The plots (shown in Fig. 3) show that the opening angle of the beam decreases with the radiation energy. Polar angle will be large for low electron energy. This information is useful in determining the optimum distance of the parabolic mirror from the beamline window. The maxima in emission occurs at $\theta = \pm 1/\gamma$, where γ is the Lorentz factor of the electron.

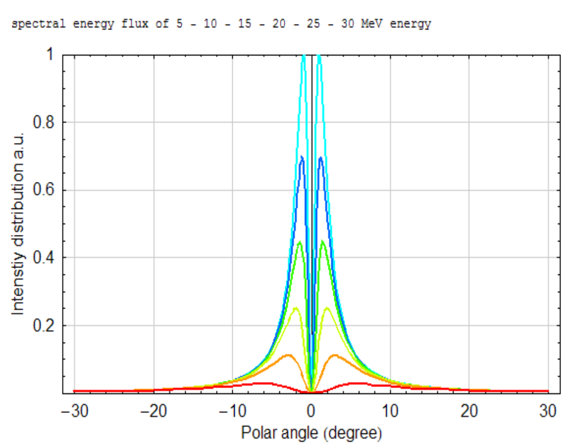

Figure 3: Transverse emission characteristics of transition radiation according to equation (1) for different electron energies of 5-10-15-20-25-30 MeV as behind the ELBE LINAC. Red curve is for 5 MeV electrons, light blue curve is for 30 MeV electrons.

SIMULATION OF OPTICAL COMPONENTS OF INTERFEROMETER

For Martin-Puplett type interferometers the response of the wire grids are found to be strongly bandwidth-limited. In order to determine the workable wavelength range for the interferometer, we compute the interference depth dependence on wavelength. After the first polarizer, the electric field direction of coherent transition radiation is polarized almost vertical. For our simulations we have used vertical electric field direction of CTR before the beamsplitter. In the experiment the beamsplitter wire grid is oriented at 45^0 with respect to the vertical electric field component. Therefore, the electric field divides into two components: (i) parallel to the wire grids and (ii) perpendicular to the wire grids (shown in Fig. 4). If the thickness **d** (20 µm) of the wires and the spacing **s** (100 µm) are small compared to the wavelength of the incident light, the module of the reflection coefficients for the vertical electric field components parallel and perpendicular to the wires can be calculated as follows [2]:

$$|R_{II}| = \left[1 + \left(\frac{2s}{\lambda}\right)^2 \ln\left(\frac{s}{\pi d}\right)^2\right]^{-\frac{1}{2}} \quad (2)$$

$$|R_{\perp}| = \left[1 + \frac{(2\lambda s)^2}{\pi^4 d^4}\right]^{-\frac{1}{2}} \quad (3)$$

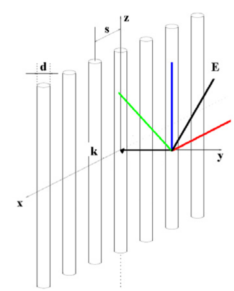

Figure 4: On the beamsplitter vertical electric field (black line) component.

A part of the radiation will also get transmitted through the beamsplitter. When the wire grids is ideal (no absorption or scattering), sum of the reflection and transmission coefficients should be one. We have simulated the vertical and horizontal electric field components after each optical component and obtained the intensities of the radiations reaching the two detectors. We have calculated the relative intensities at both the detectors as a function of frequency (0-3 THz). We have restricted the frequency range to 3 THz because it is the workable limit for the polarizers and beamsplitters. Figure 5 shows the interference depth given by the difference between the signals of the vertical and horizontal detectors.

The lower cut-off frequency at the detector input windows is about 0.5 THz. Using the Martin-Puplett interferometer we can thus measure CTR in the frequency range of 0.5-2.7 THz. This indicates that we can measure bunch lengths between 0.5 and 2 ps with our setup.

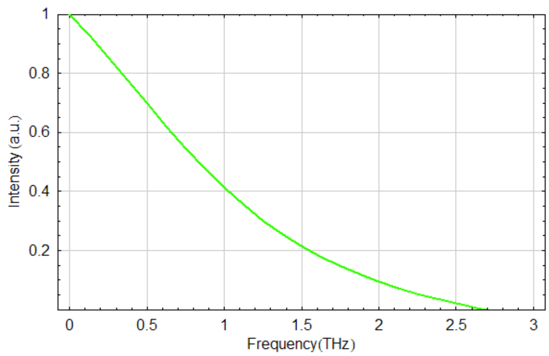

Figure 5: Spectral response of detectors signal. Response of the detectors is difference in between the vertical and horizontal detector signal.

COMPARISON BETWEEN SIMULATION AND EXPERIMENT

In this section, we will describe our analysis of the measured spectra (shown in Fig. 6) of the far-infrared CTR. The shape of the CTR pulse is a "copy" of the electron bunch shape. Measurement of the radiation spectrum give information about the bunch length.

The signal intensities measured at the vertical and horizontal detectors show that the vertical detector signal is much higher than horizontal detector signal for each scan. We have therefore normalized signals on the basis of the fact that since the detectors were identical the mean value of the data measured by the detectors should be equal and the modulation depth, i.e., the difference in the maximum and minimum will be equal as well, as the sum of the two signals must be constant. We define the difference interferogram as the difference of these amplitudes which is autocorrelation function of the radiation pulse. According to the Wiener-Khintchine theorem the fast Fourier transform of the autocorrelation function is the experimental power spectrum.

For simulation, a hypothetical Gaussian shape of the bunch is assumed. We used the general Huygens Fresnel integral in our simulation to account for the diffraction losses on the detector input windows.

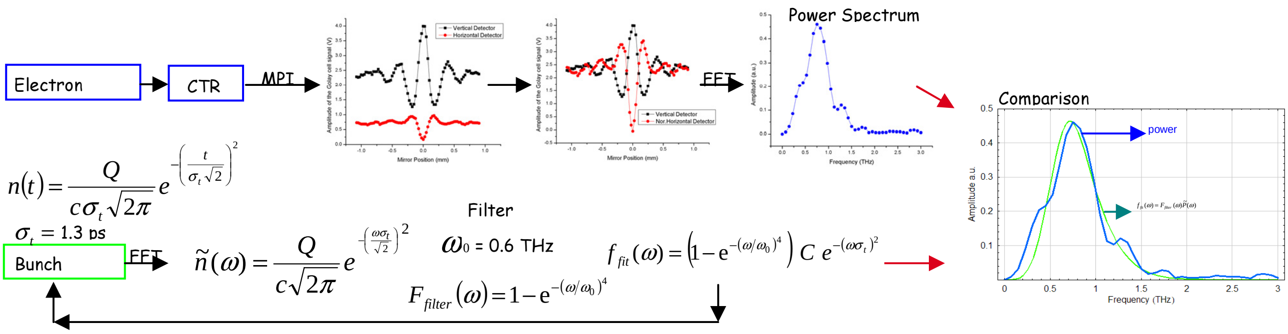

Figure 6: Analysis of measurement, comparison between simulation and experiment.

The simulated power spectrum thus consists of a product of the Fourier transform of the hypothetical Gaussian shape of the bunch and the factor accounting for the diffraction losses. This function is fitted to the power spectrum to obtain unknown parameters like RMS bunch length and the cut off frequency on the detector input window. As an example we show one of our experimental results where by fitting the spectrum we have obtained the RSM bunch length of 1.3 ps.

CONCLUSIONS

We have calculated the response of the experimental setup as a function of the CTR wavelength which is essential for correct analysis of the measured signal. We have simulated the autocorrelation function where diffraction losses at the detector windows are taken into account. From there we derive an operation range of 0.5-2 ps for the bunch length determination with our MPI. Using MPI measurements and by comparison of the experimental results with our simulations we have estimated the electron bunch lengths. If the electron bunch length is compressed below 0.5 ps we will not be able to measure it with our MPI setup.

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